3P3-4

Proceedings of Symposium on Ultrasonic Electronics, Vol. 36 (2015)
5-7 November, 2015

Structure Optimization of PZT-on-silicon Diaphragmed Highly Sensitive Ultrasound Transducer

シリコン/PZT 積層振動板による高感度超音波トランスデューサーの構造最適化

Jing Zhu†, Hiroki Makino, Tsuyoshi Okubo and Norio Tagawa
(Graduate School of System Design, Tokyo Metropolitan University)
祝 婧†，牧野 紘樹，大久保 毅，田川 憲男
(首都大学東京システムデザイン研究科)

1. Introduction

Ultrasound imaging system is widely used for medical diagnoses and non-destructive testing. The accuracy of those applications is generally required, and hence, ultrasound reception performance has to be improved so as to sensitively detect very weak echo with high frequency components. Especially, harmonics generated while ultrasound is travelling in a testing medium and its echoes are effective for high resolution imaging, but those are very weak. To capture such the weak ultrasound, recently we have proposed an FET-based micromachined ultrasound receiver (MUR), which is characterized by a PZT layer forming a diaphragm to respond to sound pressure. Its performance is ensured by the direct coupling of a PZT layer and an FET gate and by the highly sensitive output of FET driven by a piezoelectric charge of PZT. Amount of the charge generally increases with a deflection of the diaphragm, thus its design is critical to the sensitivity. We optimize the diaphragm with the thicknesses of the PZT and the silicon layers constituting the diapgram. This report descibes the dependency of these thickness on the deflection amplitude simulated by finite element method (FEM).

2. Device and Method

A square diaphragm is modeled with its layer structure as illustrated in **Fig. 1**. The body of the diaphragm is silicon and its four sides are clamped through the boundary condition of the FEM calculation. PZT is used for the piezoelectronics diaphragm performing a deflection-to-electric current conversion by its 1,3-mechanoelectric coupling. Its motion caused by the diaphragm deflection is freely allowed to deform with six modes mathematically expressed as a tensor matrix. Inter-layers couple the materials ideally not to show any misalignment in between and are set not to interfere the layers motion.

For the element optimization, mechanics models are set to analyze the relationship between the deflection amplitude and the frequency by varying diaphragm's size and the thickness ratio of the PZT/Si layer. The obtained structure is verified in terms of suitability for a working frequency and a bandwidth.

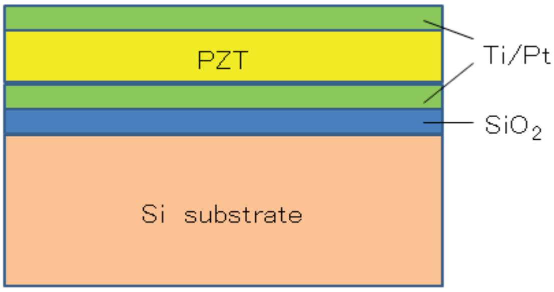

Fig. 1 Structure of PZT-on-silicon diaphragm

Table I Material properties used for FEA

Material	ρ (kg/m^3)	Y (GPa)	ν
PZT	7900	80	0.33
Si	2330	165	0.22

Material properties used in the FEM simulations are given in **Table I**. The parameters required for the structural analysis are density ρ, the Young's modulus Y, and the Poisson's ratio ν.

3. Resonance Frequency

In the MUR, the diaphragm is composed of the PZT and the silicon layers. The natural frequency of the diaphragm (also known as central frequency or a resonance frequency) is an important parameter. The equation used for calculating the resonance frequency is defined as follows:

$$f = 1.654 \frac{t}{L^2} \sqrt{\frac{Y}{\rho(1-\upsilon^2)}} \tag{1}$$

where, f, t, L are a resonance frequency, a thickness of the diaphragm and a side length of the device, respectively.

---

jing7air@gmail.com

4. Modeling and Discussion

At first, the resonance frequency and the static deformation characteristics of the PZT-on-silicon diaphragm were investigated. Its resonance frequency changes, due to their geometries and material properties. We observed the resonant frequency for the diaphragm widths ranging in 30µm–100µm, while setting the PZT and the Si thicknesses in 2µm and 4µm, respectively. The result is shown in **Fig. 2**. From this figure, it is observed that the frequency decreases with increasing the diaphragm width [1].

Dependency of the diaphragm thicknesses on the resonance frequency is shown in **Fig. 3**. The remarkable finding is that at the same thickness of the PZT layer, the thicker Si layer shows higher resonance frequency. On the other hand, at the same thickness of the Si layer, when the PZT layer's thickness changed, the resonance frequency shows different tendencies. For the case that the Si layer's thickness is in the range between 1µm and 5µm, the frequency increases with the PZT layer's thickness. Whereas, further thickens the Si layer up to 8µm, the frequency decreases with the PZT layer's thickness. Besides, the thickness of the Si layer is in the range from 5µm to 7µm, the frequency is almost constant against the PZT thickness. From these observations, we can see that the change in the Si thickness influences more significantly in the resonance frequency than the change in the PZT thickness.

By further investigation into the characteristics of the resonance frequency equation, there would be a rational interpretation. When the Si layer's thickness increased, it made the diaphragm thickness and the total stiffness increase, and as a result, the frequency increases. Oppositely, the PZT layer's thickness increases with the diaphragm thickness, which causes the decrease of the stiffness of the diaphragm. These two factors have opposite effects in the resonant frequency. Therefore, the different results as mentioned above are observed.

Figure 4 shows the PZT and the Si layers' thickness dependencies on the displacement of the diaphragm calculated by FEM simulations. The result shows that the deflection increases with decreasing the silicon layer's thickness, which means that more mechanical energy is converted into electrical energy.

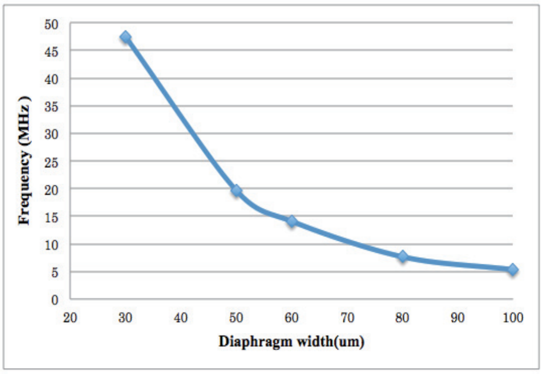

Fig. 2 Resonance frequency at various diaphragm widths

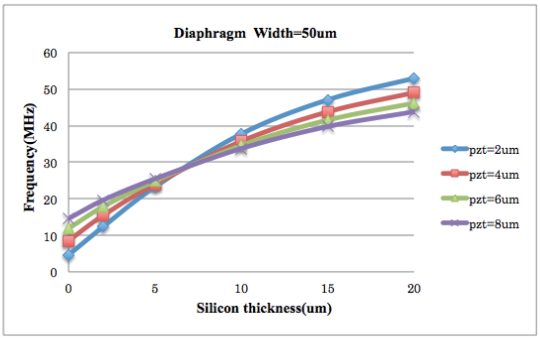

Fig. 3 Resonance frequency vs. PZT/Si layer's thickness

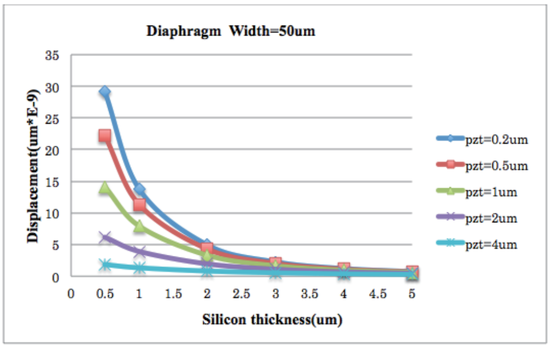

Fig. 4 Piezoelectric displacement vs. PZT/Si layer's thickness under 0.2Pa pressure

5. Conclusion

The frequency was verified to change according to Eq. 1 also in this diaphragm model. This observation is indicative that the resonant oscillation is dominated by an elastic modulus stored in the silicon layer. The piezoelectric simulation is indicative of the diaphragm vibration mechanism dominantly controlled by the PZT layer. Further optimization of the ratio of the PZT and the silicon layers' thicknesses will serve an improved MUR with a high dynamic range and wideband functionalities.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 25350569.

References

[1] P. Muralt, et al.: IEEE Trans. UFFC **52** (2005) 2276.